

# **A Musculoskeletal Model-based Assistance-As-Needed Paradigm for Assistive Robotics**

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# Nomenclature

## Formatting Style

Formatting	Description
$[\dots]^T$	Vector or matrix transpose
$\ \dots\ $	Vector norm
$ \cdot $	Scalar absolute value

## Subscript and Numbering

Symbol	Description
$k$	Number of degrees of freedom in the musculoskeletal system
$m$	Number of MTU models in the musculoskeletal system
$\mathbb{N}_1$	Set of natural numbers $\{1, 2, 3, 4, \dots\}$

## Symbol Usage

Symbol	Description	Units
$\alpha$	Muscle fibre pennation angle .....	rad
$\alpha_0$	Muscle fibre pennation angle at optimal length $L_0^m$ .....	rad
$\varepsilon^t$	Tendon strain .....	-
$\sigma$	Standard deviation .....	-
$\boldsymbol{\theta}$	Robot measured joint position vector .....	rad
$\dot{\boldsymbol{\theta}}$	Robot measured joint velocity vector .....	rad/s
$\boldsymbol{\theta}_r$	Robot reference joint position vector .....	rad
$\dot{\boldsymbol{\theta}}_r$	Robot reference joint velocity vector .....	rad/s
$a$	MTU activation .....	-
$\mathbf{a}$	MTU activation column vector .....	-
$A$	Robot assistance parameter .....	-
$b$	Robot admittance gain .....	m.s <sup>-1</sup> /N
$\mathbf{C}$	Coriolis and centripetal effects .....	N.m
$f_A^m$	Active force component in muscle fiber .....	N
$f_P^m$	Passive force component in muscle fiber .....	N
$f^t$	Tendon force .....	N
$f^M$	MTU force .....	N
$\mathbf{f}$	MTU force column vector .....	N
$\mathbf{f}^A$	MTU active force column vector .....	N
$\mathbf{f}^P$	MTU passive force column vector .....	N
$\tilde{f}_A^m(\cdot)$	Normalised MTU fiber active force-length function .....	-
$\tilde{f}_P^m(\cdot)$	Normalised MTU fiber passive force-length function .....	-
$\tilde{f}_V^m(\cdot)$	Normalised MTU fiber force-velocity function .....	-
$\tilde{f}^t(\cdot)$	Normalised MTU tendon force-strain function .....	-

$F_0^m$	Maximum isometric muscle fiber force .....	N
$F^E$	Scalar magnitude of external force .....	N
$\mathbf{F}_H$	Measured force vector between robot and human operator	N
$\mathbf{F}_E$	Measured force vector between robot and the task .....	N
$\mathbf{H}$	Mass matrix of the musculoskeletal dynamic system .....	kg.m <sup>2</sup>
$\mathbf{J}$	Robot kinematic Jacobian matrix .....	-
$\mathbf{J}_v$	Musculoskeletal kinematic Jacobian matrix .....	-
$\mathbf{K}_A$	Activation-to-force gain matrix .....	N
$K_D$	Derivative gain in robot PD controller .....	-
$K_P$	Proportional gain in robot PD controller .....	-
$\mathbf{K}_\tau$	Activation-to-torque gain matrix .....	N.m
$\mathbf{K}_{\tau i}$	The $i$ -th row of matrix $\mathbf{K}_\tau$ .....	N.m
$l^M$	MTU length .....	m
$\dot{l}^M$	MTU velocity .....	m/s
$\mathbf{l}$	MTU length column vector .....	m
$\dot{\mathbf{l}}$	MTU velocity column vector .....	m/s
$l^m$	MTU fiber length .....	m
$\tilde{l}^m$	Normalised MTU fiber length .....	-
$\dot{l}^m$	MTU fiber velocity .....	m/s
$\tilde{\dot{l}}^m$	Normalised MTU fiber velocity .....	-
$l^t$	Tendon length .....	m
$L_0^m$	MTU fiber optimal length (coinciding with $F_0^m$ ) .....	m
$L_s^t$	MTU tendon slack length .....	m
$\mathbf{L}$	MTU Jacobian matrix .....	-
$\mathbf{M}$	Mass matrix of the robot dynamic system .....	kg.m <sup>2</sup>
$q$	Generalised coordinate position .....	rad



$\dot{q}$	Generalised coordinate velocity .....	rad/s
$\ddot{q}$	Generalised coordinate acceleration .....	rad/s <sup>2</sup>
$\mathbf{q}$	Generalised coordinate position column vector .....	rad
$\dot{\mathbf{q}}$	Generalised coordinate velocity column vector .....	rad/s
$\ddot{\mathbf{q}}$	Generalised coordinate acceleration column vector .....	rad/s <sup>2</sup>
$r_i$	The $i$ -th element of vector $\mathbf{r}$ .....	m
$\mathbf{r}$	External force moment-arm column vector .....	m
$s$	MTU activation upper bound .....	-
$\mathbf{s}$	MTU activation upper bound column vector .....	-
$S_P$	Strength capability of a human operator .....	N
$S_P^{\max}$	Strength upper bound used to limit $S_P$ .....	N
$S_T$	Strength requirement of a task .....	N
$\tau^M$	Muscular joint torque .....	N.m
$\boldsymbol{\tau}^M$	Muscular joint torque column vector .....	N.m
$\boldsymbol{\tau}^A$	Active muscular joint torque column vector .....	N.m
$\tau_i^P$	The $i$ -th element of vector $\boldsymbol{\tau}^P$ .....	N.m
$\boldsymbol{\tau}^P$	Passive muscular joint torque column vector .....	N.m
$\tau_i^B$	The $i$ -th element of vector $\boldsymbol{\tau}^B$ .....	N.m
$\boldsymbol{\tau}^B$	Dynamic and gravity load torque column vector .....	N.m
$\boldsymbol{\tau}^G$	Gravity load torque column vector .....	N.m
$\boldsymbol{\tau}^E$	External load torque column vector .....	N.m
$\mathbf{u}$	Unit vector representing external force direction .....	-
$V_0^m$	MTU fiber maximum contractile velocity .....	m/s

# Abbreviations

AAN	Assistance As Needed
ADL	Activities of Daily Living
CV	Coefficient of Variation
EMG	Electromyography
IAD	Intelligent Assist Device
MM	Musculoskeletal Model
MSD	Musculoskeletal Disorder
MTU	Musculo-Tendon Unit
MVC	Maximum Voluntary Contraction
SM	Strength Model
TM	Task Model

# Abstract

## A Musculoskeletal Model-based Assistance-As-Needed Paradigm for Assistive Robotics

Robotic systems which operate collaboratively with their human operators to provide assistance are becoming reality, and many different paradigms for administering this assistance have been developed. A promising paradigm is Assistance-As-Needed, which aims to provide physical assistance specific to the individual requirements of the operator. This requires that the needs of the operator be determined, which is challenging as they depend on both the task being performed, and the capability of the operator to perform it. Current solutions use performance-based methods which critique the operator from observations obtained during tasks, and then adapt assistance based on how they performed. This approach has shown success in applications such as robotic rehabilitation. However, empirical performance-based methods have inherent limitations, primarily due to the numerous observations required before the operator's assistance needs can be determined. The ideal Assistance-As-Needed paradigm should be able to determine the operator's assistance requirements without prior observations, and with respect to arbitrary tasks.

This thesis presents a novel Assistance-As-Needed paradigm using models to estimate the assistance needs of the human operator. An optimisation model is developed which utilises a publicly available musculoskeletal model representing the human upper limb to estimate their strength, which is compared to the strength required by the task being performed to gauge their assistance requirements. An advantage of this model-based

approach is it allows effects on the operator's assistance requirements due to task and physiological factors to be predicted. Furthermore, it avoids many of the limitations faced by empirical performance-based approaches since it does not require empirical observations. The model-based paradigm is demonstrated and evaluated in a number of simulated tasks involving the upper limb. Calculated upper limb strength is analysed with respect to factors such as the limb position, the direction of force at the hand, and muscular impairment. The calculated strength is shown to predict behaviours similar to those described in the literature. Experimental evaluation is performed by implementing the paradigm on a specially developed robotic exoskeleton to govern the assistance it provides a subject in a number of experimental tasks. The model-based Assistance-As-Needed paradigm is shown to successfully govern assistance towards specific muscles when needed in the tasks performed. Means of improving the paradigm, including methods for fitting the model to the subject, and the inclusion of additional physiological factors in the calculation of their assistance requirements is discussed.